International Intercomparison of Horn Gain at X-Band

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***Abstract*—An international intercomparison of horn gain and polarization measurements at X-band has recently been completed. There were seven participating laboratories with the National Institute of Standards and Technology serving as the pilot laboratory. Two X-band pyramidal standard gain horns with a nominal gain of 22 dB served as the traveling standards. Quantities measured included on-axis fixed frequency gain at 8, 10, and 12 GHz, swept frequency gain between 8–12 GHz and polarization characteristics at the three fixed frequencies. All laboratories performed the fixed frequency-gain measurements. The swept-frequency and polarization measurements were optional, with four laboratories performing swept-frequency measurements and three laboratories measuring polarization. The results of the gain measurements generally agreed within the reported uncertainties which were of the order of 0.1 dB or less.**

I. Introduction

An international intercomparison of horn gain and polarization at X-band has recently been completed. This comparison was initiated in July 1978 by a resolution at a meeting of the High-Frequency Working Group of the Consultative Committee on Electricity of the International Bureau of Weights and Measures, and designated GT-RF 78-5.

Participants in the intercomparison were Fernmeldetechnischen Zentralamt (now Deutsche Telekom AG, Forschungs- und Technologiezentrum) (FTZ), Germany, Technical University of Denmark, Denmark (TUD), Centre National d'Etudes des Telecommunications (CNET), France, Commonwealth Scientific and Industrial Organization (CSIRO), Australia, National Physical Laboratory (NPL), UK, Van Swinden Laboratory (VSL), The Netherlands, and the National Institute of Standards and Technology (NIST), USA, which served as the pilot laboratory.

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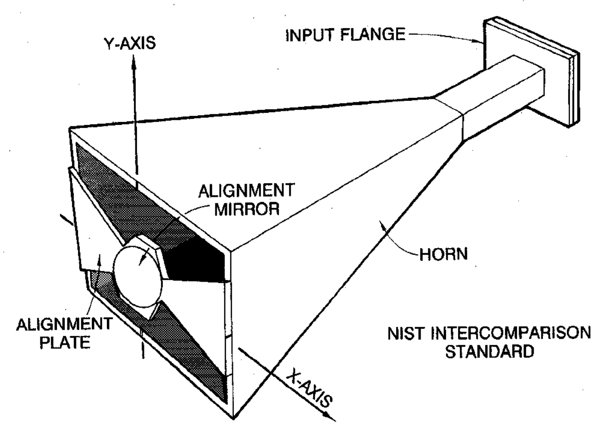


Fig. 1. Pyramidal horns used as traveling standards showing the alignment fixture and mirror used to ensure that the measurement axis was repeatable.

II. Description of the Intercomparison

The test objects for the intercomparison were two commercially available, nominally identical, 22-dB pyramidal standard gain horns of the NRL design of Slayton [1]. To ensure that the experimental conditions were identical for each test, the antennas were provided with an alignment mirror which uniquely defined the boresight direction, as illustrated in Fig. 1. To minimize horn interaction with the mounting structure, a section of microwave absorber was placed behind each horn, as illustrated in Fig. 2. The antennas were initially calibrated at NIST and subsequently two additional times, one after the intercomparison was partially completed and a final time after the completion of all other measurements.

Laboratories were invited to participate at various levels. The basic level consisted of measuring the gain of the horn at 10 and 12 GHz. In addition, a measurement at 8 GHz could also be performed. A swept-frequency gain measurement between 8–12 GHz was also available as an option. Finally, polarization parameters (axial ratio (AR), tilt angle, and sense of rotation) at 8, 10, and/or 12 GHz could also be measured as an option. Table I gives the level of participation and dates of measurement for each participating laboratory.

TABLE I
SUMMARY OF MEASUREMENTS PERFORMED AT PARTICIPATING LABORATORIES

Laboratory	Date	Fixed Frequency Gain	Swept Gain	Polarization
NIST (NBS)	'80, '82, '86, '92	8, 10, 12	8-12 GHz	A.R., Tilt, Sense
TUD	1985	8, 10, 12	8-12.4 GHz	A.R., Tilt, Sense
CNET	1988	8.2, 10, 12*	8.2-12.4 GHz	
FTZ	1987	8, 10, 12*	8-12.4 GHz	
CSIRO	1988	8, 10, 12		
NPL	1991	8, 10, 12	8-12.5 GHz	
VSL	1992	8, 10, 12		A.R.

*Antennas assumed identical, average values are reported

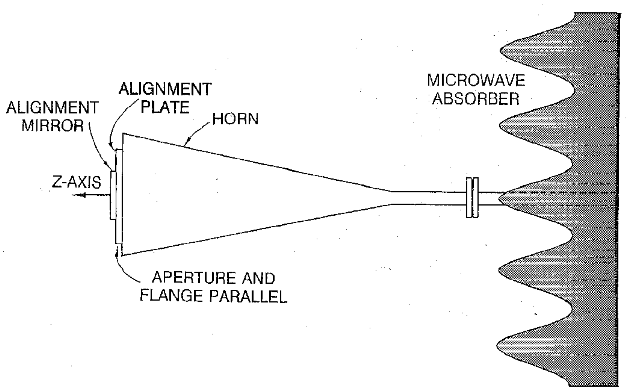


Fig. 2. Horn mounted with absorber to reduce effect of mounting structure on measurement results.

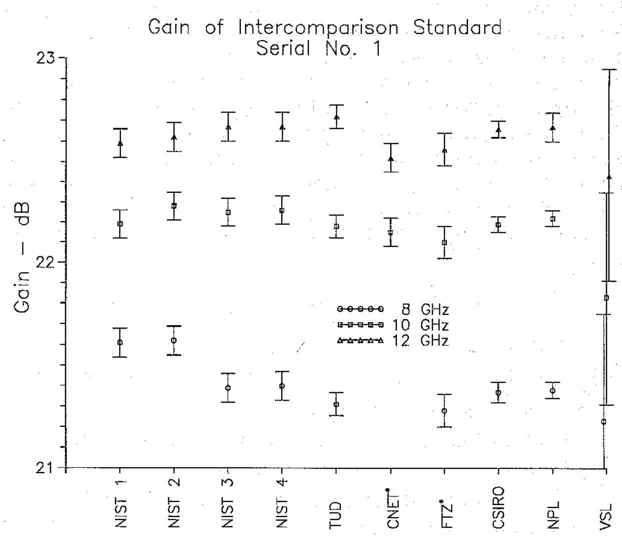


Fig. 3. Comparison of gain values at the three fixed measurement frequencies, 8, 10, and 12 GHz for traveling standard number one. Asterisks indicate gain values are averages for the two test horns. Error bars are the 2σ values as reported by the participating laboratories.

III. MEASUREMENT TECHNIQUES

NIST (USA) Description [2] and [3]

The four sets of measurements at NIST were performed using an extended three-antenna technique to allow polarization measurements. The gain products were obtained using the extrapolation technique described in [2]. The 1980 and 1982 measurements used a distance range of $0.25\ D^2/\lambda$ to $1.0\ D^2/\lambda$, while the 1986 and 1992 measurements used a distance range of $0.5\ D^2/\lambda$ to $2.0\ D^2/\lambda$. Polarization was determined using a modified three-antenna technique [3]. Three-antenna swept-frequency measurements were also performed in 1982, 1986, and 1992. These measurements were performed at a fixed distance, and the resultant swept-frequency curves corrected using measured gain and proximity correction at the fixed frequencies.

TUD (Denmark) Description [4]

Measurements were performed using a spherical near-field technique to determine pattern and directivity. The probe was a conical horn, and 90 spherical modes were used to calculate the patterns. The measurement distance was 5.742 m and data were probe corrected. Gain was calculated from directivity and the calculated wall loss for the antenna which was of the order of 0.01 dB. Spherical measurements were performed at 85 frequencies to give swept-frequency gain coverage. Polarization was obtained from the spherical measurement, the probe polarization having been previously calibrated using the three-antenna technique.

CNET (France) Description [5]

Measurements were performed assuming that the antennas were identical and employed a theoretical proximity correction based on the formulation of Chu and Semplak [6]. Mechanical and radiation pattern measurements were performed on the antennas to verify that they were, in fact, identical. The anechoic chamber has a useful volume of 5 m $\times$ 6 m $\times$ 12 m. Power ratio for the measurement was made using the insertion-loss technique. Measurements were performed at 20 distances between 2.5–4.5 m. In addition, a pair of measurements was performed at a separation increment of $\lambda/4$ to allow correction for multiple reflections.

TABLE II
GAIN OF INTERCOMPARISON STANDARDS AT 8.0 GHz

Laboratory	Gain S/N 1 (dB)	Gain S/N 2 (dB)	2σ Uncertainty (dB)
NIST (1980)	21.61	21.54	0.07
NIST (1982)	21.62	21.57	0.07
NIST (1986)	21.39	21.31	0.07
NIST (1992)	21.40	21.40	0.07
TUD	21.31	21.30	0.06
CNET*	21.35	21.35	0.07
FTZ	21.28	21.28	0.08
CSIRO	21.37	21.34	0.05
NPL	21.38	21.34	0.04
VSL	21.23	21.23	0.5

*Frequency of measurement was 8.2 GHz.

TABLE III
GAIN OF INTERCOMPARISON STANDARDS AT 10.0 GHz

Laboratory	Gain S/N 1 (dB)	Gain S/N 2 (dB)	2σ Uncertainty (dB)
NIST (1980)	22.19	22.29	0.07
NIST (1982)	22.28	22.26	0.07
NIST (1986)	22.21	22.21	0.07
NIST (1992)	22.26	22.23	0.07
TUD	22.18	22.23	0.06
CNET	22.15	22.15	0.07
FTZ	22.10	22.10	0.08
CSIRO	22.19	22.17	0.04
NPL	22.22	22.19	0.04
VSL	21.89	21.97	0.5

TABLE IV
GAIN OF INTERCOMPARISON STANDARDS AT 12.0 GHz

Laboratory	Gain S/N 1 (dB)	Gain S/N 2 (dB)	2σ Uncertainty (dB)
NIST (1980)	22.59	22.65	0.07
NIST (1982)	22.62	22.63	0.07
NIST (1986)	22.67	22.60	0.07
NIST (1992)	22.67	22.57	0.07
TUD	22.72	22.71	0.06
CNET	22.52	22.52	0.07
FTZ	22.56	22.56	0.08
CSIRO	22.66	22.61	0.04
NPL	22.67	22.60	0.07
VSL	22.43	22.39	0.5

FTZ (Germany) Description [7] and [8]

Measurements of the antennas were performed at a separation of approximately 6.6 m and gain calculated using the Friis transmission formula. The amplitude center technique of Appel–Hansen and Panicali [9], [10] was used to determine the proper separation distance for use in this formula. The

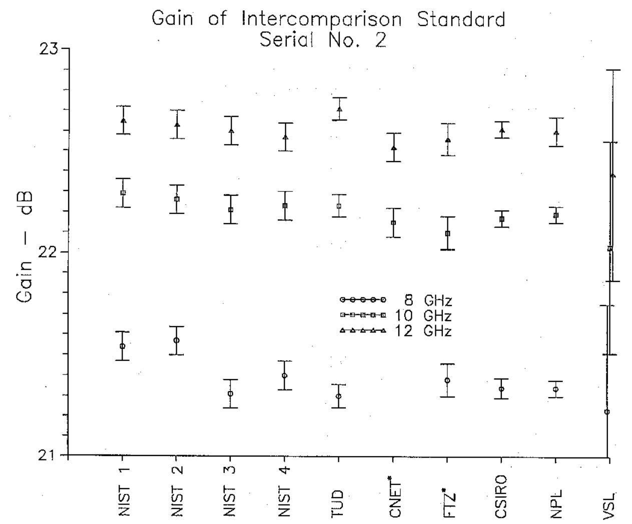


Fig. 4. Comparison of gain values at the three fixed measurement frequencies, 8, 10, and 12 GHz for traveling standard number two. Asterisks indicate gain values are averages for the two test horns. Error bars are the 2σ values as reported by the participating laboratories.

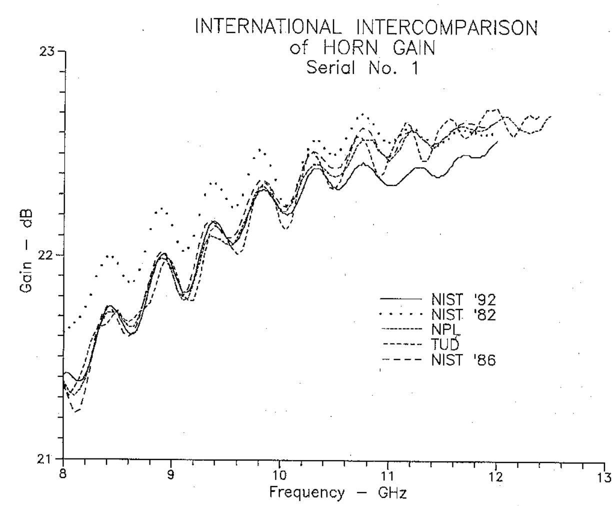


Fig. 5. Swept-frequency gain results for horn serial number one.

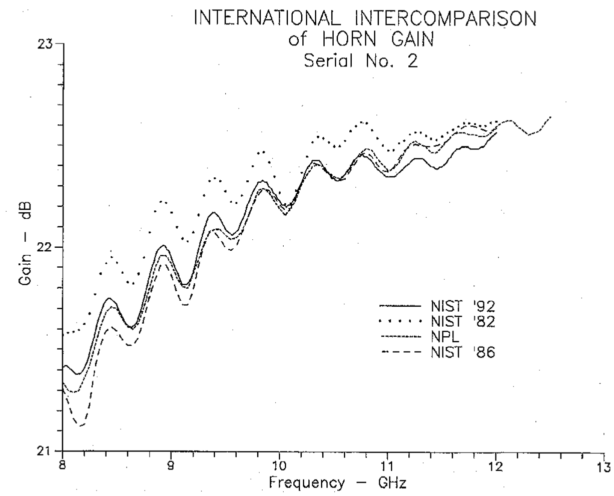


Fig. 6. Swept-frequency gain results for horn serial number two.

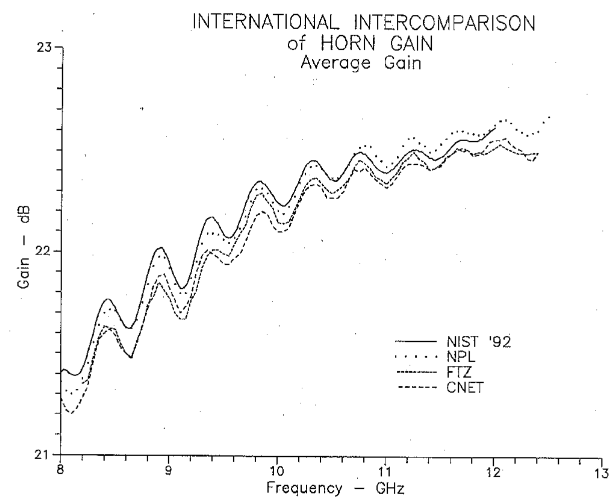


Fig. 7. Swept-frequency gain results for average gain of horns.

amplitude centers were determined by separation distance shifts of 0.64–0.72 m. Data were also smoothed to eliminate the effects of multiple reflections. The antennas were assumed to be identical.

CSIRO (Australia) Description [11]

Measurements were performed using the three-antenna technique to a suite of four antennas that comprised the two traveling antennas and two supplied by CSIRO. This gave four three-antenna sets which yielded three distinct gain determinations of each antenna. The measurements were performed in a 7 m $\times$ 5 m $\times$ 3 m anechoic chamber. Measurements were performed at separations from 0.5 D^2/λ to at least 4 D^2/λ. Data were analyzed using an extended version of the Friis transmission formula which includes a theoretically derived proximity correction [12]. This theoretical correction is then weighted in such a way as to better fit the measured gain product versus distance characteristic.

NPL (UK) Description [13]

Measurements were performed in the NPL extrapolation range of dimension 9.5 m $\times$ 4.1 m $\times$ 3.07 m. The microwave power was supplied by a synthesized sweep generator. At each measurement distance, the power transmission was measured at frequency increments of 0.05 GHz between 8.0–12.5 GHz. Thus, the swept-frequency measurements were not made at a fixed distance. They comprise 91 gain values measured by the three-antenna extrapolation technique. The resulting data are fitted to a polynomial function of inverse distance and two sinusoidal terms which represent the multiple reflection terms. The fitting process follows that of Borland [14].

VSL (Netherlands) Description [15]

Measurements were performed in an anechoic room with one open side (dimensions 5.0 m $\times$ 3.0 m $\times$ 2.4 m) at a

TABLE V
POLARIZATION OF INTERCOMPARISON STANDARDS AT 8.0 GHz

Laboratory	S/N 1			S/N 2		
	A. R. (dB)	Tilt (°)	Sense	A. R. (dB)	Tilt (°)	Sense
NIST (1980)	60 ± 2	90.3 ± 0.5	R	60 ± 2	91.5 ± 0.5	R
NIST (1982)	52 ± 2	90.7 ± 0.5	R	51 ± 2	90.5 ± 0.5	R
NIST (1992)	52 ± 2	90.9 ± 0.25	R	69 ± 2	90.8 ± 0.25	R

TABLE VI
POLARIZATION OF INTERCOMPARISON STANDARDS AT 10.0 GHz

Laboratory	S/N 1			S/N 2		
	A. R. (dB)	Tilt (°)	Sense	A. R. (dB)	Tilt (°)	Sense
NIST (1980)	43 ± 2	90.4 ± 0.5	R	44 ± 2	91.4 ± 0.5	R
NIST (1982)	44 ± 2	90.7 ± 0.5	R	45 ± 2	90.9 ± 0.5	R
NIST (1992)	44 ± 2	90.8 ± 0.25	R	45 ± 2	90.8 ± 0.25	R
TUD	44 ± 2	90.9 ± 0.03	R	45.3 ± 2	90.8 ± 0.03	R
VSL	47					

TABLE VII
POLARIZATION OF INTERCOMPARISON STANDARDS AT 12.0 GHz

Laboratory	S/N 1			S/N 2		
	A. R. (dB)	Tilt (°)	Sense	A. R. (dB)	Tilt (°)	Sense
NIST (1980)	42 ± 2	90.6 ± 0.5	R	47 ± 2	90.8 ± 0.5	R
NIST (1982)	42 ± 2	90.9 ± 0.5	R	47 ± 2	90.6 ± 0.5	R
NIST (1992)	42 ± 2	90.7 ± 0.25	R	44 ± 2	90.8 ± 0.25	R
TUD	41.8 ± 2	90.8 ± 0.03	R	46.4 ± 2	90.7 ± 0.03	R

distance of 3.5 m using the three-antenna technique using each of the two horns supplied by NIST and two smaller horns supplied by VSL. The proximity correction of Chu and Semplak [6] was employed.

IV. Results of Gain Measurements

The results of the fixed-frequency gain measurements are shown in Figs. 3 and 4 and Tables II–IV. Estimated uncertainties are indicated by the error bars as reported by the individual laboratories. Uncertainties given are 2σ values, 95% confidence level. Where coverage factors corresponding to other confidence levels are reported by the participating laboratories, the reported factor has been modified to reflect a consistent coverage factor of two.

V. Results of Swept-Frequency Measurements

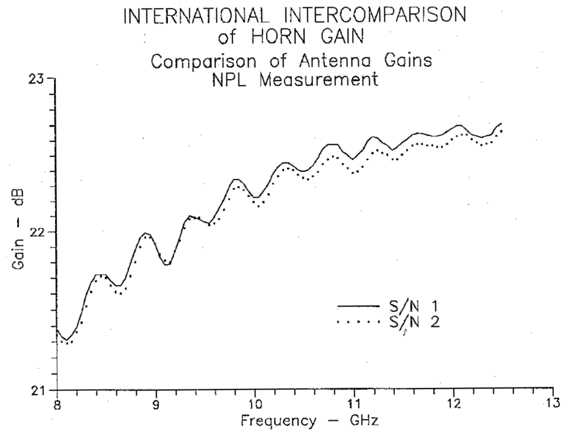
Swept-frequency measurements were performed at five of the participating laboratories. The results of the swept measurements are shown on the following plots. Figs. 5 and 6 show the results for the individual gains of antennas number one and two. One laboratory, TUD, reported individual swept-frequency gain for antenna number one only. Two laboratories, CNET and FTZ reported average gain for the antenna pair. Fig. 7 shows a comparison of these results with the average of the individual gains measured at NPL and NIST.

VI. Results of Polarization Measurements

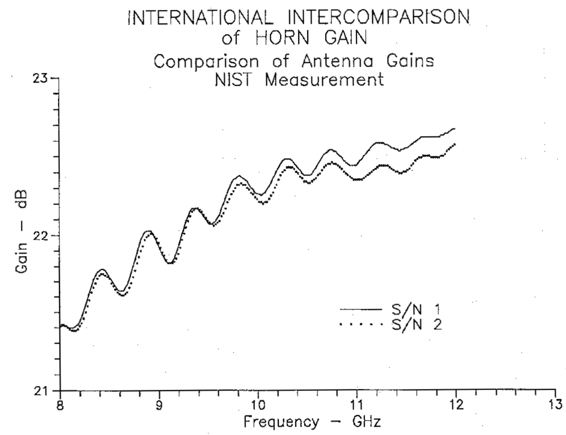
Polarization measurements were performed at only two laboratories (TUD and VSL) besides the pilot laboratory. In addition, only TUD measured the complete polarization characteristic for both antennas. Tables V–VII list the axial ratio, tilt angle, and sense of polarization (right—R, or left—L), measured by the participants for each antenna.

VII. Interpretation of Results

In general, the agreement between measurements is within the tolerance specified by each laboratory. A notable exception is at 8.0 GHz where, for the 1980 and 1982 measurements,



(a)



(b)

Fig. 8. Comparison of swept-frequency gain of horn serial number one and serial number two from measurements at (a) NPL and (b) NIST.

NIST reports approximately 0.3 dB above the values obtained by the other participants. It is now apparent that the distance range employed in the extrapolation technique was too short for these measurements. The procedure was changed to correct for this problem after the 1982 measurements. Noteworthy is the fact that several fundamentally different techniques were employed to correct for proximity effects and yielded results that agreed within the estimated uncertainties.

Polarization measurements also showed good agreement between the laboratories which participated in this phase of the measurement.

Finally, we comment on the assumption that the two test horns were identical. Fig. 8 shows the swept-frequency measurement of the two horns measured at a) NIST and b) NPL. We observe that both laboratories show similar but not identical gain versus frequency characteristics with antenna number one having a higher gain than antenna number two. Physical measurements of the antennas, however, showed the dimensions to be negligibly different. The swept-frequency measurements also indicate the importance of determining the frequency dependence of these antennas rather than relying on the nominal curves provided by Slayton [1].

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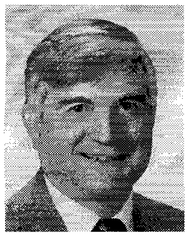
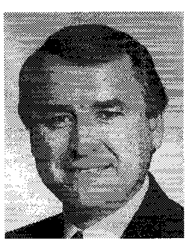
Dr. Stubenrauch in a Registered Professional Engineer. He is a member of URSI Commission A and the Optical Society of America.



Allen C. Newell (F'91) was born on October 15, 1936, in Salt Lake City, UT. He received the B.S. degree in physics from Brigham Young University, Salt Lake City, UT, in 1960, and has been involved in graduate work in physics and electrical engineering at the University of Colorado, Boulder.

He joined the NIST (formerly the National Bureau of Standards) Boulder Laboratories, CO, in 1960, and performed research in high-frequency voltage and power measurements. Since 1962, he has been involved in a variety of microwave and millimeter wave-measurement problems. He codeveloped a millimeter wave refractometer accurate to within a few parts in 10^8 and received a special award for his contributions to a millimeter wave velocity of light experiment. Beginning in 1965, He worked on the development of the planar near-field measurement technique for determining antenna characteristics from measurements made close to the antenna. He also codeveloped the generalized three-antenna extrapolation method for performing high-accuracy gain and polarization measurements of microwave antennas. He has published several reports and papers in the above areas and has taught seminars and short courses on antenna measurements at NIST, Georgia Institute of Technology, Atlanta, California State, Northridge, and The Technical University of Denmark, Lyngby. He is an internationally recognized expert in the area of near-field antenna measurements.

Mr. Newell is has served on the Administrative Committee and the Antenna Standards Committee of the Antenna and Propagation Society. He has received Bronze and Silver Medal Awards from the Department of Commerce and the Samuel Wesley Stratton Award from the National Bureau of Standards for his part in the development and dissemination of antenna measurement techniques. He has served as Group Leader of the Antenna Metrology Group and is currently the Division Chief of the Electromagnetic Fields Division at NIST.



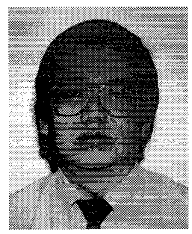
Andrew G. Repjar (M'77–SM'82) received the B.E.E., M.S., and Ph.D. degrees from The Ohio State University, Columbus, OH, in 1964, 1966, and 1970, respectively.

He is Leader of the Antenna and Materials Metrology Group in the Electromagnetic Fields Division of the National Institute of Standards and Technology, Boulder, CO where, since 1975, he has utilized both near-field and far-field measurement techniques to determine antenna parameters used in radar, satellite, and communications systems. Since 1992, he is also responsible for leading a metrology program on the characterization of the microwave properties of materials. These materials include thin films, substrates, and other materials used in antenna lenses, radomes, microwave absorbers, and microstrip antennas. Prior to 1975, he worked at Rockwell International, Columbus, OH, and at the ElectroScience Laboratory at The Ohio State University. He has published many reports and papers in the antenna metrology areas and has given lectures in short courses on antenna measurements at NIST and industrial facilities. His fields of interest include electromagnetic theory, antenna theory, properties of materials, radar cross section metrology, and satellite communication measurements.

Dr. Repjar received the Department of Commerce Silver Medal and Bronze Medal Awards, for his outstanding contributions in extending the practical utility of NIST-developed methods for measurements on antennas, in 1989 and 1987, respectively. He served on the Administrative Committee in the Antennas and Propagation Society from 1993–1995. He also serves on the Antenna Standards Committee, and chairs the Committee on Support for AP-S History. In 1991 he served as President of the Antenna Measurement Techniques Association, and in 1989–1990 as Vice President of the same organization.

Katie MacReynolds (S'82–M'83) was born in Manistee, MI, on September 11, 1950. She received the B.S. and M.S. degrees in electrical engineering from the University of Colorado, Boulder, in 1983 and 1991, respectively.

From 1983 to 1985 she was in the Broad-Band Antenna Group at Texas Instruments, Inc., Plano, TX, working in design and fabrication of electrically small antennas used in direction-finding systems. For the next two years, she was a member of the National Telecommunications and Information Administration with the Spectrum Use and Measurements Group, Boulder, CO, involved in the measurement of frequency-spectrum utilization of radar and land-mobile radio. Since 1987, she has been with the Antenna and Materials Metrology Group in the Electromagnetic Fields Division of the National Institute of Standards and Technology, Boulder, CO. Her experience involves precision antenna measurements, focusing on measurement and analysis of near-field measurement techniques, extrapolation gain and polarization technique, and probe calibration. She is the technical contact for antenna measurement and calibration services for the group.



Douglas T. Tamura was born in Denver, CO, on February 22, 1955. He attended Colorado School of Mines, CO, in 1973, Colorado State University, Fort Collins, from 1973 to 1975, and Metropolitan State College, Denver, from 1976 to 1982.

He began his career at the National Institute of Standards and Technology (NIST), Boulder, CO, in 1973 as a Student Apprentice, and for many years worked in various laboratories throughout. He was involved in properties of dielectric materials prior to joining the Antenna Measurements Group, at NIST, in 1980. His main area of interest is in antenna measurements and calibrations, primarily the on-axis extrapolation gain measurement.

Flemming Holm Larsen was born in Copenhagen, Denmark, in 1948. He received the M.Sc. and Ph.D. degrees in electrical engineering from the Technical University of Denmark, Lyngby, Denmark, in 1973 and 1982, respectively.

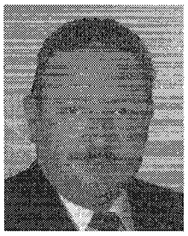
In 1974, he joined the Electromagnetics Institute of the Technical University of Denmark, Lyngby, as a Research Associate, and was then named Assistant Professor and Associate Professor in 1985 and 1989, respectively. He participated in the development of a spherical near-field antenna measurement system for the European Space Agency and was the author of the first spherical near-field transformation code employing the full probe-pattern correction. He was a contributing author to a book on spherical near-field antenna measurements edited by J. Hansen and published by Peter Peregrinus in 1988. He was a Consultant for TICRA, Copenhagen, Denmark, in the field of near-field antenna measurements. He passed away suddenly in 1992.

J. Lemanczyk (S'75–M'80) was born in Montréal, PQ, Canada, in 1953. He received the B.Sc.E.E. degree from Concordia University, Montréal, Canada, and the M.Eng. degree from McGill University, Montréal, in 1975 and 1978, respectively.

He was a Visiting Researcher at the Electromagnetics Institute, Technical University of Denmark, Lyngby, Denmark, twice during the period 1977 through 1980. From 1980 to 1995, he worked at the Electromagnetics Institute on the development and applications of spherical near-field antenna testing. He was responsible for the operations of the TUD-ESA Spherical Near Field Antenna Test Facility at the Electromagnetics Institute. Since July 1995, he has held the position of Senior Antenna Engineer in the Electomagnetic Compatibility and Antenna Measurements Section of the Electromagnetics Division of the European Space Agency's space research and technology center (ESTEC) in Noordwijk, The Netherlands.

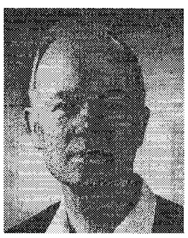
R. Behe, photograph and biography not available at the time of publication.

G. Portier, photograph and biography not available at the time of publication.



J. C. Zehren was born in France in 1941. He received the baccalauréat, in 1959, the degree of license of sciences, in 1966, and the diploma of doctor in electronic option high frequencies, in 1969, all from the University of Sciences, Toulouse, France.

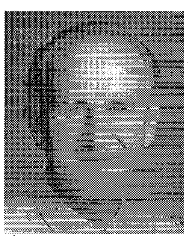
From 1967 to 1970, he was with the high school ENSAE where he worked on microwave devices and ferroelectric materials. He joined the National Center of Study in Telecommunication (CNET) of French Ministry PTT in 1970 where he was working in the design of radio-link antennas and standard horns. He is currently working on satellite antennas and is responsible for the antenna subsystem of the French satellite program, Telecom 2.



Heinrich Hollmann was born in Germany in 1937. He received the Dipl.-Ing. degree in electrical communication from the Technical University of Aachen, Aachen, Germany in 1965.

Since 1965, he has been working as a Research Associate in the Forschungszentrum im FTZ der Deutschen Bundespost Telekom, Darmstadt, Germany. He is currently engaged in research work on antennas. His special fields of activity are antennas for mobile radio communications and anechoic chambers. He was also involved with exposure technique and instrumentation in bioelectromagnetics, until his retirement in 1996.

Mr. Hollmann is a member of the German Commission A of the International Scientific Radio Union (URSI).



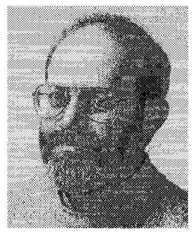
John D. Hunter received the B.E. (Hons.) and Ph.D. degrees in electrical engineering from the University of Canterbury, New Zealand.

For more than 20 years he has been with the Commonwealth Scientific and Industrial Organization (CSIRO) in Sydney where he now leads the radio frequency and microwave project of the National Measurement Laboratory. His present interests are centered on electromagnetic field and antenna standards and electromagnetic compatibility measurements.

David G. Gentle was born in Kingston upon Thanes, England, in 1963. He received a B.A. degree in physics, in 1986, from Christ Church, Oxford, U.K.

Since 1986, he has been working in the Antenna Measurements Group at the National Physical Laboratory, Teddington, England. During that time, his main area of work has been the measurement of the gain of microwave antennas by the three-antenna technique. More recently, he has been developing facilities to characterize probes for near-field scanning.

Mr. Gentle was a joint recipient of the Ayrton Premium from the IEE, UK, in 1995. He also won a Bostock Exhibition from Christ Church, Oxford, U.K.



Jan P. M. de Vreede was born in Pijnacker, The Netherlands, in 1945. He received the M.S. and Ph.D. degrees in physics from the Rijksuniversiteit Utrecht, The Netherlands, in 1970 and 1977, respectively. He was involved in Postgraduate work at the University of Utrecht, from 1977 to 1983, in high-precision microwave spectroscopy using FM-detection techniques.

During his military service (1976–1977), he was involved in the development of an infrared heterodyne radar prototype. In 1983, he joined the Electricity & Magnetism Department of the NMi Van Swinden Laboratorium, Delft, The Netherlands (the Dutch National Standards Laboratory). Since 1988, he has been Deputy Manager there. His main interests are the development and maintenance of high-frequency standards and calibration facilities and has been involved in several international comparisons in these fields.